PICTURES AT A CONFLAGRATION: MAPPING THE MAVERICK PRESCRIBED FIRE

Larry K. Clark, Graduate Research Assistant
Stephen R. Yool, Assistant Professor
Department of Geography and Regional Development
Pyrogeography Research Laboratory
Box 2 Harvill Building
The University of Arizona, Tucson, AZ 85721
Phone: (520) 621-1652
E-mails: lclark@u.arizona.edu; yool@skydog.arizona.edu

ABSTRACT

The Madrean Archipelago of sky islands in the southwestern United States and northern Mexico relies on fire to help regulate and maintain biodiversity, yet only limited fire research has been conducted in the region. Developing new tools and techniques for visualizing change across such diverse and expansive landscapes is essential as natural resource management responsibilities expand, increased oversight efficiency is required, and, technology rapidly evolves. However, recording information about firescapes in wilderness areas is often difficult due to accessibility, weather conditions, safety concerns, and large areal extent. Remote sensing techniques are thus used increasingly to gather data on fire activity at ecosystem scales. We demonstrate the viability of commercially available digital terrain and remotely-sensed datasets for mapping the Maverick prescribed fire. The Maverick fire was ignited mechanically by the USDA Forest Service on June 24 and 25, 1997, in the southern Peloncillo Mountains. Multispectral band ratio transformation and linear transformation techniques enhanced prefire and postfire Landsat 5 Thematic Mapper imagery. These enhancements were used to map the fire scar and canopy consumption classes. The wetness enhancement of the Kauth-Thomas transformation depicted spatial variations in fuel moisture content before and after the fire.

Keywords: biogeography, fire mapping, Madrean Archipelago, remote sensing, U. S. Southwest

INTRODUCTION

As in other parts of the country, fire on the landscape of the American Southwest has declined significantly during the past century for several reasons. Policy decisions by various jurisdictions (Leopold, A. S., et al. 1963; Schullery, P. 1989; Arno, S. F., and Brown, J. K. 1991) as well as changes in the composition of plant communities as a result of overgrazing, logging, and non-native plant invasion (Pyne, S. J. 1982; Bahre, C. J. 1991) have been influential deterrents to fire. Today, the judicious re-kindling of fire on the landscape is generally viewed as an asset, rather than a liability, to natural resources management (Hardy, C. C., and Arno, S. F. 1996). Understanding the temporal and spatial variability of fire behavior and ecosystem response is critically important for fire to be an effective tool. We argue remote sensing technologies offer a valuable and viable means for gaining this knowledge.

Our overall goal is to analyze relationships among topography; prefire vegetation type, distribution, and density; and fire scar using satellite imagery as the primary data source along with other digital and non-digital ancillary data. Previous studies have shown that using data from the Landsat Thematic Mapper (TM) is effective to map change from disturbance at a scale sufficient to discern ecosystem-level variation (Collins, J. B., and Woodcock, C. E. 1996; White, J. D. et al., 1996; Patterson, M. W., and Yool, S. R. 1998). This paper focuses primarily on enhancement techniques for extracting the fire scar from satellite imagery, and on a canopy consumption classification map derived from fire scar imagery. Fuel moisture content, as characterized by the wetness feature of the Kauth-Thomas transformation, is introduced as a variable of fire behavior.

THE MAVERICK STUDY SITE

The Maverick study site is located in the Peloncillo Mountains of the Madrean Archipelago, which gets it name, in part, from the Madrean biotic province (Brown, D. E. 1994). Stretching along a roughly north-south axis from the Mogollon Rim to the Sierra Madre Occidental, the Madrean Archipelago is a complex of alternating mountain ‘islands’ and valley ‘seas’, that are either barriers or bridges for colonization by various species, depending on dispersion patterns, transport capabilities, and adaptability (Warshall, P. 1995). The biodiversity found throughout this complex is unique and extensive (McLaughlin, S. P. 1995). Consequently, the *entire region* has been recognized as one of several threatened areas worldwide that should be preserved and protected for its *overall* richness of species and habitats (Schmidt, K. 1996).

The Peloncillo range, a subtle north-south arc crossing the southern Arizona/New Mexico border, is one of about 40 sky island complexes that comprise the Madrean Archipelago. Rising from the Chihuahuan Desert on the valley floor, the Maverick site straddles the Arizona/New Mexico border just north of the international border with Mexico. The abundant diversity typical of sky islands is found here and provides for greater variation in fire behavior and ecosystem response than in more homogeneous forest landscapes.

The Maverick site supports plant communities ranging from semidesert mesquite grasslands at lower elevations to dense Madrean evergreen woodlands of oak, juniper, and pinyon at upper reaches, with riparian corridors of sycamores and other deciduous tree species interspersed throughout (Sundt, P. 1997; Muldavin, E. et. al 1998). Such stratification along an elevational gradient, in this case from 1264 m to 1964 m, is characteristic of sky island complexes. Development of these plant communities is due partly to the region's cycle of mild winters and warm, wet summers interrupted by a dry spring hiatus. The site is volcanic in origin (McIntyre, D. H. 1988), characterized by slopes from flat to nearly vertical, with predominantly west and south aspects.

THE MAVERICK FIRE

The Maverick fire was more than four years in planning and involved a variety of federal, state, and local agencies and organizations. The purpose of the fire was to create a mosaic of burned and unburned areas, reducing invasive trees and shrubs and increasing herbaceous plant materials, while returning fire to the ecosystem (Encinas, E. 1997). Mechanically ignited by the USDA Forest Service on June 24 and 25, 1997, the fire smoldered into mid-July. The total area of the site involved nearly 40,000 acres of public and private land; an unprecedented areal extent for a management-ignited prescribed fire in the Southwest. Eight spatially dispersed ignition sites were originally planned within a primary fire containment area of 17,000 acres; only seven of these sites were ignited in 1997.

DATA AND METHODS

The principal data used for mapping and analyzing the Maverick fire scar in this study was acquired by the Landsat 5 TM. This multispectral sensor completes a full cycle every 16 days, traveling in a near-polar, sun-synchronous orbit at a nominal altitude of 705 km and covering a swath 185 km wide with a nominal spatial resolution of 30 m. Radiance data is collected simultaneously in seven spectral bands, three visible and four infrared (IR), including one thermal IR band (with a nominal spatial resolution of 120 m). All six non-thermal bands were used in this study.

Scene Selection

A June 19, 1995, TM scene from our archives was identified initially as the prefire dataset. This dataset was temporally proximate and consistent phenologically with the ignition dates of June 24 and 25, 1997.

Selection of the postfire TM scene was influenced by several factors: First, the postfire scene needed to be as temporally proximate as possible to the end of fire activity. Second, the scene needed to be cloud-free. Third, the scene needed to precede the annual Southwest summer monsoon: This summer rainy season begins around the Fourth of July and ends about Labor Day. Daily afternoon thunderstorms can produce heavy, localized precipitation, especially in the sky island mountain ranges. Along with high temperatures, the abundant rainfall produces a vigorous seasonal green-up, particularly where herbaceous plants dominate. This greening can obscure quickly any trace of fire activity. Ultimately, a scene from July 3, 1997 was selected. Although the Forest Service determined the fire had not burnt out completely until July 12, 1997, and monsoon activity did not commence until later in the month, most of the fire activity had occurred by July 3. No cloud-free scenes were available after July 3 until October, well after the fire and the green-up resulting from the monsoon.

As luck would have it, the TM passed over the site on the morning of June 24, 1997, the first day of ignition. (Because the study site lies in the overlap of two different satellite paths, the temporal difference is less than 16 days). Due to its eloquent timeliness, we subsequently acquired that TM scene as the prefire dataset. The scene's header file noted the acquisition time as 172114 (GMT); approximately 10:21 a.m. local time (MST), not long after mechanical ignition began. The discovery of this scene was extremely fortuitous because it offered an extremely tight temporal frame for analysis; it was completely serendipitous because the burn had been postponed numerous times; and, it was potentially unprecedented because the scene could provide fuel information essentially *at the moment of ignition*. Timing *is* everything!

Preprocessing

Radiometric correction and atmospheric compensation were performed on all three TM datasets prior to analytical image processing, using ERDAS Imagine v. 8.2 and 8.3. A suite of United States Geological Survey (USGS) 30m digital elevation models (DEMs) was mosaicked and used as ground reference for geometric registration. Because the June 24, 1997, scene had not yet been identified and obtained, an absolute registration of the June 19, 1995, TM scene to the DEMs was performed. Subsequently, relative registrations of the July 3, 1997, TM scene to the June 19, 1995, TM scene, and the June 24, 1997, TM scene to the July 3, 1997, TM scene were completed. Resampling of TM scenes to 30.0 m pixels was done to correspond to the resolution of the DEMs.
The Iterative Band Ratioing (IBR) technique was chosen to minimize contrast reduction due to atmospheric scattering. This technique is appropriate for scenes containing patterns resulting from significant topographic shadowing unrelated to land cover classes (Crippen, R. E. 1989). The logic is that two scatter-free bands will, when ratioed, show no topographic shadowing. Because scattering produces residual shadowing in ratioed bands, excess ‘scattered’ digital numbers (DNs) can be subtracted out. For this study, the visible TM bands 1, 2, and 3 were adjusted; minimal atmospheric scattering occurs in the other non-thermal bands (Avery, T. E., and Berlin, G. L. 1992).

Enhancement Techniques

Fire reduces scene reflectance due to the collapse of plant cell structure, a net loss in fuel moisture content, and the production of ash. Extracting the fire scar for visualization involved simple image differencing after enhancing each pair of prefire and postfire images. Six different enhancements were performed: Principal Components Analysis (PCA), Kauth-Thomas transformation (KT), Normalized Difference Vegetation Index (NDVI), Modified Soil Adjusted Vegetation Index (MSAVI), a ratio of TM band 7 to TM band 4, and a simple differencing of near-infrared (NIR) TM band 4. The enhanced prefire image was subtracted from the enhanced postfire image. Decreased reflectance was expressed as negative values within the dynamic range of values for the resulting scene.

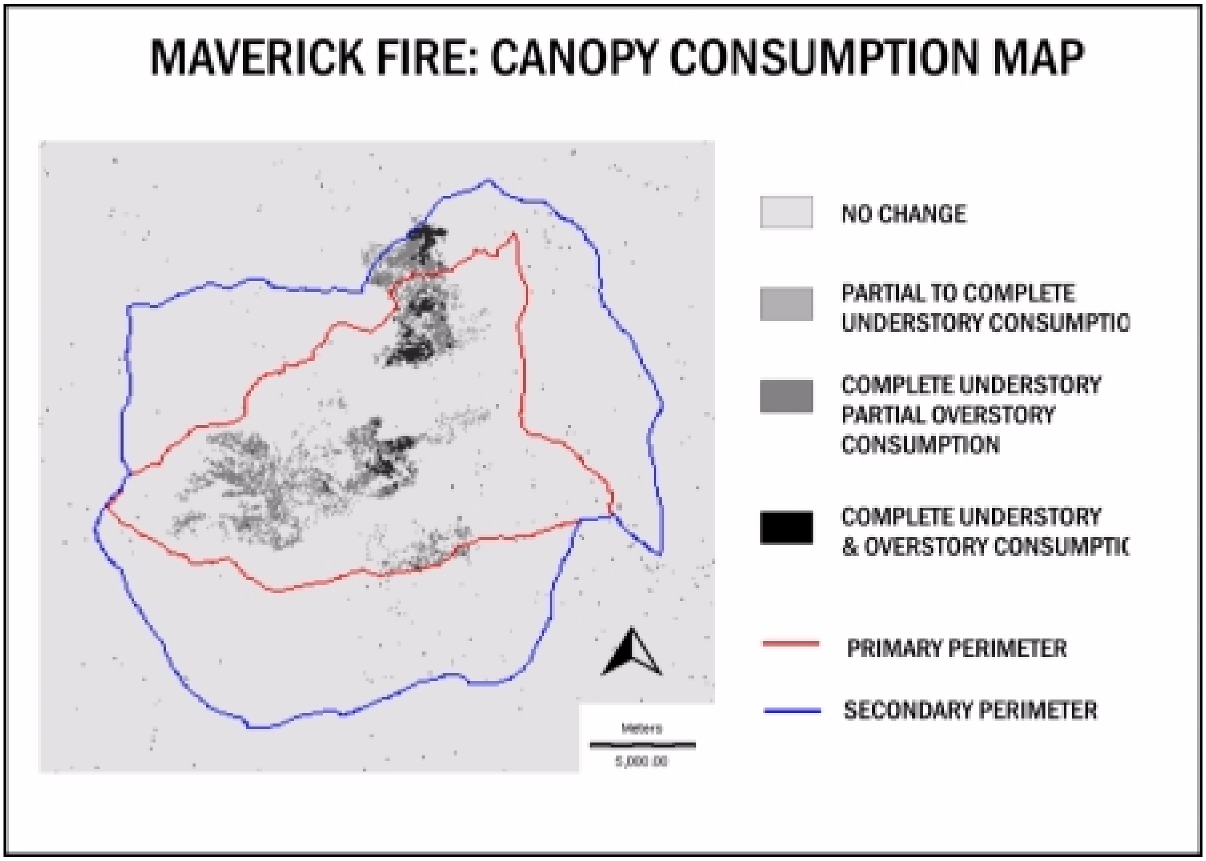
PCA and KT are both orthogonal transformations, wherein all six non-thermal TM bands are combined, the data compressed and separated into uncorrelated components (Jensen, 1996). In PCA, the first three components generally explain between 95% and 98% of the variance within all six non-thermal input bands. Of the six features produced by the KT transformation, the first three, wetness, brightness, and greenness, were used for this study. NDVI and MSAVI are vegetation indices using TM bands 3 (visible red) and 4 (NIR) in a ratio. MSAVI was developed to adjust for exposed soil background noise prevalent in satellite imagery of arid and semi-arid regions (Qi, J., et al. 1994). In addition to the information provided by the specific bands used, band ratio techniques are important methods of enhancement because they reduce differential illumination caused by topographic shadowing.

Once each fire scar image was created, its dynamic range of differenced values was standardized using a statistical Z-transformation. This produced a unitless measure within a standard range, thereby permitting comparison between techniques producing otherwise different unit measures within different ranges.

Canopy Consumption Map

A map of fire behavior, characterized by canopy consumption, was constructed through a semi-supervised classification. Aggregation of dynamic range values into four canopy consumption classes was based on true-color ground and mid-altitude aerial photography, as well as the investigators’ personal knowledge of the site. The four classes were (1) no change, (2) partial to complete understory consumption, (3) complete understory and partial overstory consumption, and (4) complete understory and overstory consumption.

The choice to classify the fire scar based on understory/overstory consumption rather than severity was intentional: Severity is a highly subjective and value-laden term, as evidenced by the discussion which ensued during the 1999 Joint Fire Science Conference and Workshop. Landscapes, as a whole, may exhibit similar, fundamental processes; but, ecosystems in different regions manifest these processes differently. Fire behavior in mixed conifer forests of the Northern Rockies is not the same as in Madrean evergreen woodlands of the Southwest; likewise, their ecosystem responses are different. The difficulty in assessing se-



verity rests not only on the landscape changes that occur, but also on the time frame over which these changes are measured.

During this study, such changes occurred very rapidly. The vigorous green-up resulting from added soil nutrients and monsoon activity occurred within 60 days. Increased herbaceous plant material was a desired objective of the fire. While some overstory canopy remained on many oak trees immediately following the fire, these plants experienced leaf-drop over the winter months and partial canopies disappeared by early spring 1998. These trees had been top-killed. However, during subsequent site trips in late spring and summer of 1998, nearly all oak trees observed were resprouting from the trunk base. This response is typical of oak species that dominate upper elevations of the site (Fischer, 1995). The fire had moved swiftly through the area with little lag time. Limited litter and organic soil matter were present; consequently soil sterilization was not a factor. Because the fire was not hot enough to eliminate most standing snags, the fire may have increased fuel loads for the site. Classifying these variables objectively in terms of severity would be difficult at best.

RESULTS

The TM band 7 / TM band 4 ratio had the greatest dynamic range of values after standardization and produced the most visually distinctive fire scar image. The other enhancements ranked in the following order, based on contrast clarity: simple differencing of TM band 4, PCA component 2, KT greenness, MSAVI, and NDVI. The exceptional quality of the TM band 7 / TM band 4 ratio image permitted classification of the fire scar into the canopy consumption classes described above.

Understanding differences in functional response among TM band wavelengths is important when examining land cover change. In arid and semi-arid regions, it is common to have significant areas of exposed soil or rock within plant communities. This contributes "noise" to the overall vegetation signal for each affected pixel. Fluctuations in soil and vegetation moisture content, influenced by seasonal precipitation regimes in these regions, also change reflectance. Band selection for regional land cover change detection studies should consider the individual contributions and combined impact of vegetation, soil, and water on spectral response.

In the most successful fire scar extraction, mid-IR TM band 7 enhanced changes in soil and fuel moisture content, while NIR TM band 4 detected changes in plant cell structure produced by the fire. Choosing enhancements employing only two vegetation-related bands, such as visible red TM band 3 (chlorophyll pigment reflectance) and NIR TM band 4 (plant cell structure reflectance), produced different and less visually compelling results. Typically, a collapse of plant cell structure precedes a decrease in leaf chlorophyll content. Most NIR reflectance occurs in the structural spongy mesophyll layer at the interface between mesophyll cells and air spaces composing this layer. As the layer collapses, NIR reflectance decreases. Because NIR reflectance lies beyond the visual spectrum, this decline is imperceptible to the human eye. A reduction in chlorophyll content occurs later, resulting in a decrease in green reflectance and an increase in red reflectance, producing a gradual change in leaf color from green to yellow to red-brown. During fire, this entire process is accelerated significantly.

Simple differencing of postfire and prefire TM band 4 (NIR) performed better than the NDVI, which used both TM bands 3 and 4 in a ratio and produced a less distinctive fire scar. The MSAVI, a similar vegetation index developed to compensate for background noise from exposed soil typical in arid and semi-arid regions, faired only slightly better than the NDVI. The differenced image of the greenness feature of the KT transformation, based on chlorophyll reflectance activity, produced a fire scar image exhibiting the range of change in greenness throughout the *entire* minimum bounding rectangle of the scene. Further isolating the fire scar may improve this enhancement. PCA component 2, which used all six TM bands and therefore collectively included information about vegetation, soil, and water, also performed better than the vegetation indices and the KT greenness enhancements. These results confirm that plant cell structure is a better indicator of change from fire activity than is chlorophyll content.

The day-of-fire TM scene provided an unprecedented opportunity to inspect differences in the spatial variability of fuel moisture content through the wetness feature of the KT transformation. As plant structure changed so too did moisture content. Areas where fire activity altered the understory and overstory canopies indicate decreased fuel moisture content. Additional statistical analysis of this feature is planned.

CONCLUSIONS

Prescribed fire as a force of change can be an important asset in land management, but its use must be judicious, its potential as a mechanism of change respected, and its impacts well understood. Once a management ignited fire is conducted or a natural fire is allowed to burn within a desired prescription, the consequences are often long-lasting, perhaps irrevocable. State-of-the-art computer technology and commercially available data resources offer new and potentially important opportunities to accomplish fire management objectives, most notably through timely, high resolution visual aids. Increased fire habitat information enables land managers to make more informed policy decisions regarding land use and maintenance, whether for wilderness preservation, ranching, recreation, or other initiatives. This is critically important, as the role of fire in ecosystem development becomes better understood.

The distinctive geophysical qualities and unique biodiversity of the Peloncillo sky island complex are fundamentally and inextricably linked to fire, whether natural or anthropogenic, as a biogeographical process. Using fire as a tool to manipulate and manage the land requires a basic understanding of the spatial and temporal relationships that exist and influence fire behavior and ecosystem response. Because little fire research has been conducted in the Southwest, especially in the lower elevations of these stratified sky island ecosystems, results of this study expand the base of knowledge about fire as an agent of change in the Madrean Archipelago and are important considerations in developing a comprehensive land management plan for the borderlands region.

Several basic conclusions can be drawn from this phase of the Maverick prescribed fire study. Of six image enhancement techniques tested, the TM band 7 / TM band 4 ratio expresses best the dynamic range of fire scars in TM data, permitting classification into four categories of canopy consumption. The wetness feature of the Kauth-Thomas transformation represents, in this case, spatial variation in fuel moisture content before and after the fire. Changes in wetness are related to structural changes and canopy consumption by the fire. Finally, remote sensing enables visualization and spatial analysis of fire. While site knowledge and ground reference data remain critical, remotely sensed data can make a significant contribution to fire-related ecosystem management. As sensor resolution improves and data become more affordable, the contribution made by these technologies will increase as well.

This project was funded by the Southwestern Borderlands Ecosystem Research Program, USDA Forest Service, Rocky Mountain Research Station, in cooperation with The University of Arizona.

REFERENCES CITED

Arno, Stephen F., and Brown, James K. (1991). Overcoming the Paradox in Managing Wildland Fire. *Western Wildlands*, Spring, pp. 40-46.

Avery, Thomas E., and Berlin, Graydon L. (1992). *Fundamentals of Remote Sensing and Airphoto Interpretation*, Prentice Hall, Inc., Upper Saddle Brook, NJ, p. 142.

Bahre, Conrad J. (1991). *A Legacy of Change: Historic Human Impact on Vegetation in the Arizona Borderland*. The University of Arizona Press, Tucson.

Brown, David E., ed. (1994). *Biotic Communities: Southwestern United States and Northwestern Mexico*. University of Utah Press, Salt Lake City, p. 13.

Collins, John B., and Woodcock, Curtis E. (1996). An Assessment of Several Linear Change Techniques for Mapping Forest Mortality Using Multitemporal Landsat TM Data. *Remote Sensing of Environment, 56*: 66-77.

Crippen, Robert E. (1989). Development of Remote Sensing Techniques for the Investigation of Neotectonic Activity, Eastern Transverse Ranges and Vicinity, Southern California. Ph.D. dissertation. University of California, Santa Barbara.

Encinas, Edwardo. (1997). *Maverick [Prescribed Burning] Plan, 1997*. USDA, Forest Service, Southwest Region, Douglas Ranger District, Douglas, AZ.

Fisher, William C., compiler. (1995). *The Fire Effects Information System*. USDA, Forest Service, Intermountain Research Station, Intermountain Fire Sciences Laboratory, Missoula, MT.

Hardy, Colin C., and Arno, Stephen F. (1996). *The Use of Fire in Forest Restoration*. INT-GTR-341. USDA, Forest Service, Intermountain Research Station, Ogden, UT.

Jensen, John R. (1996). *Introductory Digital Image Processing: a Remote Sensing Perspective*. Prentice Hall, Inc., Upper Saddle River, NJ, pp. 172-187.

Leopold, A. S., et. al. (1963). Wildlife Management in the National Parks. *American Forests*: 69(4): 32-35, 61-63.

McIntyre, D. H. (1988). *Volcanic Geology in Parts of the Southern Peloncillo Mountains, Arizona and New Mexico*. Bulletin 1671. U. S. Geological Survey, Denver.

McLaughlin, Steven P. (1995). An Overview of the Flora of the Sky Islands, Southeastern Arizona: Diversity, Affinities, and Insularity. In *Biodiversity and Management of the Madrean Archipelago: The Sky Islands of Southwestern United States and Northwestern Mexico*. RM-GTR-264. USDA, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO, pp. 60-70.

Muldavin, Esteban, Archer, Vince, and Neville, Paul. (1998). *A Vegetation Map of the Borderlands Ecosystem Management Area*. Final Report.

Patterson, Mark W., and Yool, Stephen R. (1998). Mapping Fire-Induced Vegetation Mortality Using Landsat Thematic Mapper Data: A Comparison of Linear Transformation Techniques. *Remote Sensing Environment, 65*: 132-142.

Pyne, Stephen J. (1982). *Fire in America: A Cultural History of Wildland and Rural Fire*. University of Washington Press, Seattle, pp. 514-529.

Qi, J., Chehbouni, A., Huete, A. R., Kerr, Y. H., and Sorooshian, S. (1994). A modified soil adjusted vegetation index (MSAVI). *Remote Sensing of Environment, 48*:119-126.

Schmidt, Karen. (1996). Rare Habitats Vie for Protection. *Science*, *274*(5289): 916-918.

Schullery, Paul. (1989). The [Yellowstone] Fires and Fire Policy. *Bioscience, 39*: 686-694.

Sundt, Peter. (1997). Report to the Malpai Borderlands Group: Pre-Fire Vegetation Sampling at the Maverick Burn Project, 1996. Unpublished report.

Warshall, Peter. (1995). The Madrean Sky Island Archipelago: A Planetary Overview. In *Biodiversity and Management of the Madrean Archipelago: The Sky*

Islands of Southwestern United States and Northwestern Mexico. RM-GTR-264. USDA, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO, pp. 6-18.

White, Joseph D., Ryan, Kevin C., Key, Carl C., and Running, Seven W. (1996). Remote Sensing of Forest Fire Severity and Vegetation Recovery. *International Journal of Wildland Fire*, *6*(3): 125-136.